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Doubly heavy baryon production at polarized photon collider

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Abstract

We study the inclusive production of doubly heavy baryon Ξ_{cc} at polarized photon collider. Our results show that proper choice of the initial beam polarizations may increase the production rate of Ξ_{cc} approximately 10%.

Key words: Doubly heavy baryon, NRQCD, Linear Collider, polarization

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The doubly heavy baryon production is an important topic in both experiments and theoretical studies. SELEX collaboration has observed the doubly heavy baryon Ξ_{cc} [1, 2, 3]. Many theoretical works have been done in [4, 5, 6, 7, 8, 9, 10, 11, 12]. However, the production rate and decay width measured at SELEX are much larger than most of the theoretical predictions. So, it is necessary to study the production mechanism more precisely. At the future International Linear Collider (ILC), backscattered laser light may provide very high-energy photons [13]. In (un)polarized photon photon fusion, the doubly heavy baryon production is possible with certain rates. The process $\gamma\gamma \to H_{QQ}X$ may play an important role in the production mechanism of doubly heavy baryon.

The production of doubly heavy baryon can be divided into two steps: the first step is the perturbative production of a heavy quark pair. For two identical heavy quark system, there are two states contributing to the doubly heavy baryon production, one state is with the heavy quark pair in $^3S_1$ and color triplet, the other is with the pair in $^1S_0$ and color

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sextet. The second step is the transformation of the heavy quark pair into the baryon, which is nonperturbative. Since a heavy quark has a small velocity in the rest frame of the baryon, we can use non-relativistic QCD (NRQCD) to handle the transformation [14]. Two hadronic matrix elements are defined for the transformation from the two states [9, 15]. In refs. [4, 5, 6, 7, 8] the inclusive production of doubly heavy baryons has been studied and only the contribution from quark pair in $^3S_1$ and color triplet is taken into account. According to the discussion in [9], one should include the contribution from both color triplet and color sextet. In refs. [9, 10, 11], the production of doubly heavy baryons for e^+e^- and hadron-hadron colliders are studied by considering the contribution from the two states. The inclusive production of H_{QQ} at unpolarized $\gamma\gamma$ collider is investigated in [12]. In this letter, we investigate the inclusive production of doubly heavy baryon at polarized photon collider. It is found that proper choice of the initial beam polarizations may increase the production rate of Ξ_{cc} up to 10%.

The inclusive production of doubly heavy baryon H_{QQ} by photon scattering can be described as

$$\gamma(p_1,\lambda_1)+\gamma(p_2,\lambda_2)\to H_{QQ}(k)+X, \tag{1}$$

where p_1, p_2 and k are respectively the momenta of the corresponding particles, λ_1 and λ_2 are the helicities of the photons. X is the unobserved state, and we can always divide it into a nonperturbative part X_N and a perturbative part X_P. At leading order, X_P consists of two heavy anti-quarks $\bar{Q}$. With the same notation as that in refs.[9, 12], one can obtain the differential cross section for the process of eq.(1)

$$\begin{aligned} d\hat{\sigma}(\hat{s},\lambda_1,\lambda_2) \;=\;& \frac{1}{4}\frac{1}{2\hat{s}}\frac{d^3\mathbf{k}}{(2\pi)^3}\int\frac{d^3p_3}{(2\pi)^3 2E_3}\frac{d^3p_4}{(2\pi)^3 2E_4}\int\frac{d^4k_1}{(2\pi)^4}\frac{d^4k_3}{(2\pi)^4}\frac{1}{2}A_{ij}(k_1,k_2,p_3,p_4,\lambda_1,\lambda_2) \\ & \cdot\frac{1}{2}(\gamma^0 A^\dagger(k_3,k_4,p_3,p_4,\lambda_1,\lambda_2)\gamma^0)_{kl}\int d^4x_1 d^4x_2 d^4x_3 e^{-ik_1\cdot x_1-ik_2\cdot x_2+ik_3\cdot x_3} \\ & \cdot\langle 0|Q_k(0)Q_l(x_3)a^\dagger(\mathbf{k})a(\mathbf{k})\bar{Q}_i(x_1)\bar{Q}_j(x_2)|0\rangle, \end{aligned} \tag{2}$$

where k_1, k_2 denote the momenta of the internal heavy quarks, and p_3, p_4 the momenta of the anti-quarks. i, j are Dirac and color indices, and $Q(x)$ is the Dirac field for the heavy quark. The summation over the final state's spins and colors are implied here, and $\hat{s}=(p_1+p_2)^2$. The factor $1/4$ is because of the identical phtons and anti-quarks. $a^\dagger(\mathbf{k})$ is the creation operator for H_{QQ} with three momentum $\mathbf{k}$. The contribution of eq.(2) can

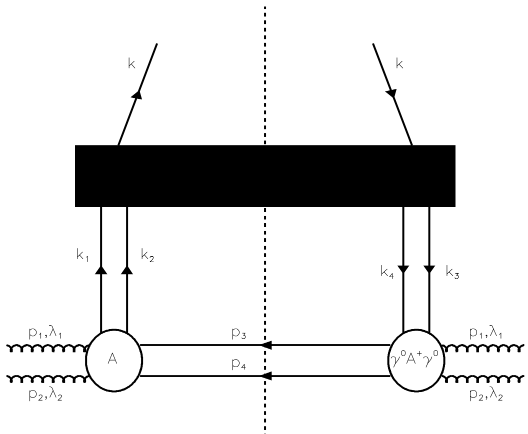

Figure 1: Graphic representation for the contribution in eq.(2), the black box represents the Fourier transformed matrix element, the dashed line is the cut and $k_4 = k_1 + k_2 - k_3$.

be represented graphically by Fig.1. In the framework of NRQCD, at the zeroth order of the relative velocity between heavy quarks in the rest frame of H_{QQ}, we can handle the hadronic matrix element as in [12]. Then, the cross section for $\gamma(p_1,\lambda_1)+\gamma(p_2,\lambda_2) \to H_{QQ}(k)+\bar{Q}(p_3)+\bar{Q}(p_4)+X_N$ process can be expressed as

$$\hat{\sigma}(\eta,\lambda_1,\lambda_2) = \frac{\alpha^2\alpha_s^2 e_q^4}{m_Q^2}[f_1(\eta,\lambda_1,\lambda_2)\frac{h_1}{m_Q^3} + f_3(\eta,\lambda_1,\lambda_2)\frac{h_3}{m_Q^3}], \tag{3}$$

where m_Q is the mass of the heavy quark, α and α_s are the fine structure constant and strong coupling, $e_q = 2/3(-1/3)$ for up(down)-type quark, and $\eta = \hat{s}/(16m_Q^2) - 1$. h_1 (h_3) represents the probability for a QQ pair in ${}^1S_0$ (${}^3S_1$) state and in the color state of 6 ($\bar{3}$) to transform into the baryon [9, 12], and they should be determined by nonperturbative QCD. Under NRQCD, h_1 and h_3 are at the same order. h_3 can be related to the non-relativistic wave function at the origin, i.e., $h_3 = |\Psi_{QQ}(0)|^2$. The numerical results for the scaling functions $f_1(\eta,\lambda_1,\lambda_2)$ and $f_3(\eta,\lambda_1,\lambda_2)$ are displayed in fig.2. One can notice f_1 and f_3 do not depend on m_Q explicitly[3].

The total effective cross section for doubly heavy baryon production at a photon col-

[3]All the results in [12] had left out a factor 1/4.

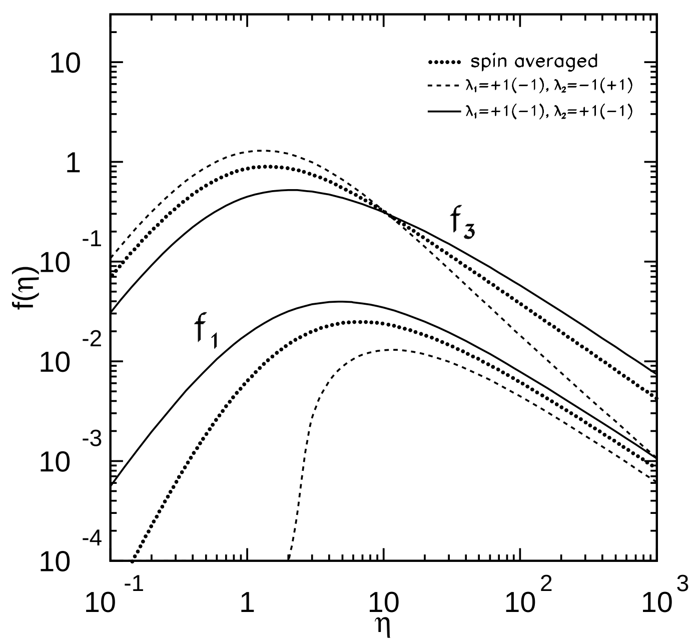

Figure 2: The scaling function $f(\eta)$.

lider can be written as

$$d\sigma(S) = \int_0^{y_{max}} dy_1 \int_0^{y_{max}} dy_2 \, f_\gamma^e(y_1, P_e, P_L) \, f_\gamma^e(y_2, P_e, P_L) d\hat{\sigma}(\hat{s}, \lambda_1, \lambda_2) \tag{4}$$

with the normalized energy spectrum of the photons

$$f_\gamma^e(y, P_e, P_L) = \mathcal{N}^{-1}[\frac{1}{1-y} - y + (2r-1)^2 - P_e P_L x r (2r-1)(2-y)], \tag{5}$$

where $\sqrt{S}$ is the e^+e^- CMS energy, $\mathcal{N}$ the normalization factor, $P_e(P_L)$ the polarization of the electron (laser) beam, $r = y/(x - xy)$, and y is the fraction of the electron energy transferred to the photon in the center-of-mass frame. It has the following range

$$0 \leq y \leq \frac{x}{x+1} \tag{6}$$

with

$$x = \frac{4E_L E_e}{m_e^2}, \tag{7}$$

where m_e is the electron mass and E_e (E_L) the energy of the electron (laser) beam. In order to avoid the creation of an e^+e^- pair from the backscattered laser beam and the low energy laser beam, the maximal value for x is $2(1+\sqrt{2})$. In the calculation, we adopt the following parameter values

$$E_e = 250 GeV, \quad E_L = 1.26 eV, \quad m_e = 5.11 \times 10^{-4} GeV. \tag{8}$$

The differential cross section $d\hat{\sigma}(\hat{s}, \lambda_1, \lambda_2)$ is evaluated with polarizations

$$\lambda_i = P_\gamma(y_i, P_e^{(i)}, P_L^{(i)}), i = 1, 2, \tag{9}$$

where the function $P_\gamma(y, P_e, P_L)$ is the polarization of photons resulting from Compton backscattering with energy fraction y, which is

$$P_\gamma(y, P_e, P_L) = \frac{1}{f_\gamma^e(y, P_e, P_L)\mathcal{N}} \{x r P_e [1 + (1-y)(2r-1)^2] - (2r-1) P_L [\frac{1}{1-y} + 1 - y]\}. \tag{10}$$

For consistency, we use the same values as taken in [12]

$$\begin{aligned} &m_c = 1.8 GeV, && \alpha = \frac{1}{137}, \\ &\alpha_s(\mu = 2m_c) = 0.20, && |\Psi_{cc}(0)|^2 = 0.039 GeV^3. \end{aligned} \tag{11}$$

$h_1(GeV^3)$		0	0.039	0.039
$h_3(GeV^3)$		0.039	0	0.039
$(P_{e1},P_{e2};P_{L1},P_{L2})$	spin averaged	8.30 (fb)	0.88(fb)	9.18 (fb)
	$(0.85,0.85;-1,-1)$	7.89(fb)	0.80(fb)	8.69 (fb)
	$(0.85,0.85;+1,+1)$	9.04 (fb)	0.98(fb)	10.02 (fb)
	$(0.85,-0.85;-1,+1)$	7.77 (fb)	0.83(fb)	8.60 (fb)
	$(0.85,-0.85;+1,-1)$	8.46 (fb)	0.91(fb)	9.37 (fb)

Table 1: Results for the effective cross section of Ξ_{cc} at $\sqrt{S} = 500GeV$.

Numerical results for the total effective cross section of Ξ_{cc} are given in Table 1. One can notice photon polarization is an important asset. The choice $(P_{e1},P_{e2};P_{L1},P_{L2}) = (0.85,0.85;+1,+1)$ can increase the production rate of Ξ_{cc} by approximately 10%. One can also find that the contribution from the color sextet QQ pair is about 10% of that from the color triplet one if $h_1 = h_3$. We also calculate the distributions of $cos\theta$, x and x_T for Ξ_{cc}, which are given in Fig.3, 4 and 5 respectively. Here, θ and x are defined in e^+e^- CMS, where θ is the angle between the moving direction of Ξ_{cc} and that of the beam. $x = 2E/\sqrt{S}$ and $x_T = 2P_T/\sqrt{S}$, with E and P_T the energy and transverse momentum of Ξ_{cc} respectively.

To summarize, we investigate the production of the doubly heavy baryon Ξ_{cc} at polarized photon collider. The production rate of Ξ_{cc} can be increased about 10% with the initial beam polarizations $(P_{e1},P_{e2};P_{L1},P_{L2}) = (0.85,0.85;+1,+1)$. The enhancement is almost equal to the contribution from the the color sextet. The precise measurement of Ξ_{cc} at polarized photon collider will be helpfull to understand the doubly heavy baryon production mechanism.

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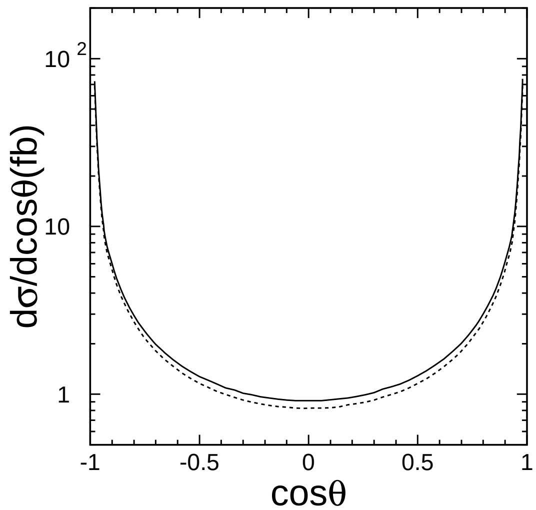

Figure 3: $cos\theta$-distributions with $h_3 = h_1 = |\Psi_{cc}(0)|^2$, the solid line for $(P_{e1}, P_{e2}; P_{L1}, P_{L2}) = (0.85, 0.85; +1, +1)$, the dashed for spin averaged.

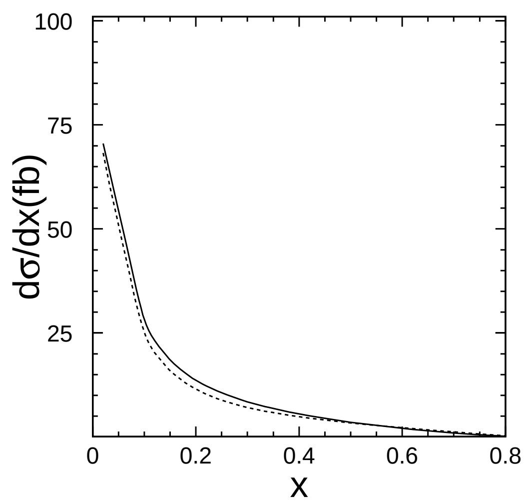

Figure 4: Same as Fig.3, but for x-distributions.

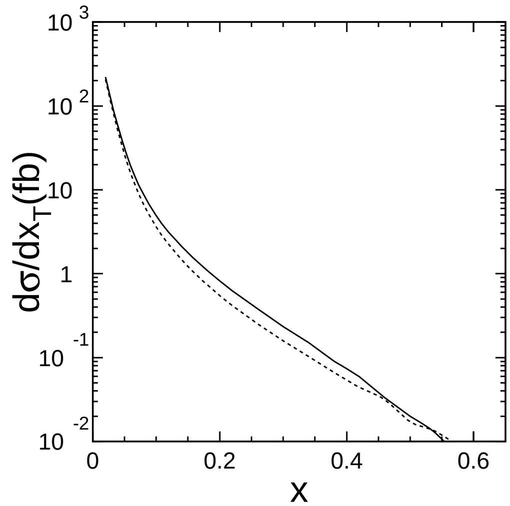

Figure 5: Same as Fig.3, but for x_T-distributions.

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